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Predicting the Performance of Long Distance
Tropospheric Communication Circuits

by

A. P. Barsis, K. A. Norton and P. L. Rice



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Table of Contents

	<u>Page</u>
Summary	
1. Introduction	1
2. Initial Discussion of System Power Requirements.....	2
3. Variability of Hourly Median Basic Transmission Loss.....	4
4. Determination of System Power.....	5
5. Prediction of the All Day-All Year Distribution of Expected Transmitter Power.....	7
6. The Concept of Service Probability.....	9
7. Conclusions	15
8. Acknowledgements	16
Appendix.....	17

SUMMARY

Comparison of calculated and measured values of transmission loss for tropospheric propagation paths shows that there is an appreciable amount of uncertainty in the prediction process. Departures of observed from predicted values may be regarded as normally distributed when expressed in decibels, and this paper considers methods of estimating these standard deviations.

In order to predict the performance of a communication system over a given path, it is necessary to define the grade of service, the time availability of this grade of service and the reliability of the predictions. The short-term (within-the-hour) signal fading is conveniently included in the definition of the grade of service, in terms of a required hourly median r.m.s. -carrier to r.m.s. -noise ratio. Next, the time availability of a given grade of service is specified in terms of the percentage of hours in a year that this minimum carrier-to-noise ratio is exceeded. To determine the time availability it is necessary to obtain the distributions with time of hourly medians for the path with given geometrical and meteorological characteristics.

In this paper the three concepts, grade of service, time availability, and reliability of prediction are brought together in a single graphical representation. The graph has two probability scales; the ordinate shows the percentage of hours service is available (time availability), and the abscissa shows the service probability (reliability of the prediction), where each curve corresponds to a system with given operating characteristics such as transmitter power, antenna size, etc. Each curve could therefore be labeled by a figure representing installation and operating costs, and various systems may thus be compared on the basis of cost versus probability of successful operation.

Predicting the Performance of Long Distance Tropospheric Communication Circuits

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1. Introduction

In a recent paper Rice, Longley, and Norton^{1/} presented a formula for the prediction of the cumulative distribution of the hourly median basic transmission loss expected on a tropospheric propagation path. To make such a prediction it is necessary to know the radio frequency, the length of the path, the antenna heights above sea level as well as their heights above the "local" terrain, the distances from the transmitting and receiving antennas to their $4/3$ earth radio horizons on the great circle path, the heights of these radio horizons above sea level and the winter-afternoon surface values of the refractivity of the atmosphere at these radio horizons.

As an example, Fig. 1 shows the profile of a path for which a point-to-point tropospheric scatter link has been proposed. This path from Sidi Slimane Air Base (Morocco) to Moron Air Base (Spain) has been chosen as an example because transmission loss measurements are available for it, and the terminal and path characteristics as well as the results of the measurements have been described previously^{2, 3/}.

^{1/} P. L. Rice, A. G. Longley, and K. A. Norton, "Prediction of the cumulative distribution with time of ground wave and tropospheric wave transmission loss," NBS Report 5582, June, 1958

^{2, 3/} A. P. Barsis and R. S. Kirby, "Long distance tropospheric propagation measurements between North Africa and Spain (Parts I & II)," NBS Reports 5067 and 5524, May 15 and Oct. 15, 1957

Fig. 2 gives the median of the hourly median basic transmission loss for this path as a function of frequency and for two antenna heights, predicted for an average winter afternoon hour on the basis of the method given in Ref. 1. With this information available, how does the engineer complete the design of his scatter link? In particular, the engineer must decide on (1) the optimum radio frequency, (2) a transmitter power, (3) appropriate antennas, and (4) a diversity system. In the course of making these decisions he should also decide whether the predictions presented in Fig. 2 are of adequate accuracy or whether they should be supplemented by further transmission loss measurements. In the case of transmission loss measurements a determination has to be made of how well the measured path and the parameters of the test circuit represent the conditions under which the permanent installation will operate.

2. Initial Discussion of System Power Requirements

For the design of a complete system the basic transmission loss over the path is not the only factor which determines the optimum frequency. One has to consider dependence on frequency of the receiver characteristics (usually expressed by an effective noise figure) and of the transmission line losses. Any complex diversity system will also contain filters, diplexers and similar components with frequency-dependent insertion losses. Another important factor is the minimum required radio frequency r.m.s. carrier to r.m.s. noise ratio. This is principally a function of the type of modulation employed, the desired short-term (within-the-hour) circuit reliability, the rate of fading of the r.f. carrier, the order of diversity employed, and the method of combining the individual signals of the diversity system. Finally, the gain of large antennas deteriorates at large distances as a function of the ratio of minimum scattering angle to half-power beam width. The effective path antenna gain therefore is also a function of frequency for a fixed antenna size, as the half-power beam width decreases with increasing frequency.

An earlier paper by Norton^{4/} contains a simple formula for the

^{4/} K. A. Norton, "Point-to-point radio relaying via the scatter mode of tropospheric propagation," Trans. IRE on Comm. Systems, Vol. CS-4, No. 1, pp. 39-49, March, 1956

determination of the transmitter power for a communication link if all of the factors outlined above are known. This expression reads:

$$P_t = L_b - G_p + F + L_t + R + B - 204 \quad (1)$$

where

P_t = transmitter power in decibels relative to one watt

L_b = basic transmission loss over the path in decibels

G_p = path antenna gain in decibels

F = effective receiver noise figure in decibels

L_t = transmission line and associated losses, in decibels

R = pre-detection r. m. s. carrier to r. m. s. noise ratio in decibels, for the bandwidth, type of modulation, and order of diversity used

$B = 10 \log_{10} b$, where b is the total bandwidth in cycles per second (including the effect of drift between transmitter and receiver oscillators)

$204 =$ a constant equal to $-10 \log_{10} kT$, where k is Boltzmann's constant, and the reference temperature T is taken to be 288.44° Kelvin

For a long-distance tropospheric path the terms F , L_t , R and B are determined by the choice of equipment and the desired capacity of transmitting intelligence; they are frequency dependent, but other-

wise may be considered fixed as soon as that choice has been made.* The terms L_b and G_p , however, are not only dependent on path geometry, frequency, and average atmospheric conditions, but also subject to statistical time and location variability. It is not the purpose of this paper to discuss the various theories which aim to explain long-distance tropospheric propagation, but it is essential that the time and location variability be taken into account in making performance predictions.

3. Variability of Hourly Median Basic Transmission Loss

For practical purposes all statistical time variability may be lumped into the basic transmission loss term L_b , and the path antenna gain considered fixed as a function of the path constants, antenna size, and frequency. In other words, we assume that the variation of P_t with time is the same as that of L_b , and independent of G_p ; this is probably not strictly true and deserves further study. In considering the time variability of basic transmission loss a distinction is usually made between short-term (within-the-hour) and long term (hour-to-hour) variations. It is known from theory and has been confirmed by experiments that the short-term variations of a tropospheric signal received over a long path usually produce approximately a Rayleigh distribution of the available power received by the receiving antenna. Therefore the effect of the short-term variations may readily be included in the R term of the transmitter power equation, and thus only a short-term median value of field strength (or transmission loss) value need be considered. This median value is conveniently taken over the time of one hour. Thus the statistically variable portion of basic transmission loss may be defined as its hourly median value L_{bm} . The long-term variability of basic transmission loss is given by the hour-to-hour variation of L_{bm} as discussed below.

It was shown in Ref. 1 how the analysis of a great quantity of measured field strength data led to the concept of time blocks. Tropospheric scattering is expected to be the most likely mode of

* This is not strictly true as the carrier-to-noise ratio R as defined above is a function of the carrier (short-term) fading rate and thus also of the frequency. For the purpose of this study, however, a typical short-term fading characteristic is assumed to be included in the determination of R , and its statistical variations are ignored except for an uncertainty factor to be discussed below.

propagation during winter afternoons (time block 2), and for this reason the practice has been established of calculating values of hourly median basic transmission loss for the conditions corresponding to this time block. The value L_{bm} calculated in accordance with (3.2) of Ref. 1 is a median of hourly median values, applicable to winter afternoons (time block 2). Its expected range for other time blocks or groups of time blocks is given by the $V(p, \theta)$ curves of Ref. 1 (Figs. 2 - 12).

The $V(p, \theta)$ curves have as their reference the hourly median basic transmission loss value L_{bm} as calculated for time block 2. In the most general case L_{bm} is determined as the combination of the scatter loss L_{bms} and the diffraction loss L_{bd} (see 3.2 of Ref. 1). However, in some cases, if the distance is sufficiently large, the diffraction field is negligible in comparison with the field produced by scatter, and L_{bm} is then very nearly equal to the scatter loss L_{bms} .

A tabulation of the time blocks is shown in Table I below:

Table I

Time Blocks

<u>No.</u>	<u>Month</u>	<u>Hours</u>
1	November-April	0600-1300
2	November-April	1300-1800
3	November-April	1800-2400
4	May-October	0600-1300
5	May-October	1300-1800
6	May-October	1800-2400
7	May-October	0000-0600
8	November-April	0000-0600

4. Determination of System Power

As an example of the calculation of system power requirements the Sidi Slimane-Moron path (see Fig. 1 for its profile) will be used. It is to be based on 24 voice channels, several of which may be loaded

with up to 16 teletype channels each (60 words per minute, start-stop, 7-unit code) by the usual multiplex methods. A design reliability corresponding to less than 1 in 10,000 teletype character errors should be obtained; incidentally, this also approximately provides a 99 percent or better short-term reliability of voice transmission. These requirements may be termed the "specified grade of service;" it will be shown later that it is desirable to calculate the probability that a specified grade of service or better is obtained during a given percentage of all hours. Antenna sizes to be considered include 28 ft. and 60 ft. parabolic reflectors for frequencies above 300 Mc, and arrays of Yagi or similar type antennas for lower frequencies designed for 18 db gain over an isotropic radiator. A quadruple diversity (space-frequency) FM system will be assumed and this automatically provides stand-by facilities at reduced power by virtue of having dual transmitting and receiving equipment at each terminal.

The median winter afternoon (time block 2) basic transmission loss L_{bm} as defined above and the path antenna gain G_p have been calculated in accordance with the methods of Ref. 1 using the applicable path parameters and atmospheric constants. L_{bm} is shown as a function of frequency for two antenna heights on Fig. 2.

Design data for the effective noise figure F and the line losses L_t from (1) have been estimated from manufacturers' specifications and a recent paper by Watt, et al^{5/} provides estimates for the carrier-to-noise ratio R and the bandwidth factor B . These four quantities may also be tabulated, or shown graphically as functions of the carrier frequency. Substituting all known data in (1), tables or curves of the median time block 2 (winter afternoon) transmitter power P_m are obtained as a function of carrier frequency, and Fig. 3 shows such curves applicable to the sample path for various types of antennas.

It should be noted here that the increase in free-space antenna gain with frequency for parabolic radiators does not fully compensate for the increase of transmission loss, noise figure, line losses, and

^{5/} A. D. Watt, E. F. Florman, and R. W. Plush, "Carrier-to-noise requirements for teletype communications via a fading U.H.F. carrier," NBS Report 5585 (in preparation)

antenna-to-medium coupling loss. Thus Fig. 3 shows pronounced broad minima of P_{ms} for the fixed antenna sizes considered. These minima indicate optimum frequencies (for this particular path) of 740 Mc for 28 ft. and 450 Mc for 60 ft. parabolic reflectors.

5. Prediction of the All Day-All Year Distribution of Expected Transmitter Power

In the previous section the required transmitter power P_m for the average winter afternoon hour was determined as a function of the system requirements, antenna size, and frequency. For the sample path the optimum operating frequencies read from Fig. 3 are as follows:

<u>Antenna Type</u>	<u>Optimum Frequency Mc</u>	<u>Transmitter Power for the Average Winter Afternoon P_m in db above 1 watt (dbw)</u>
18 db Yagis	70*	27.5
28 ft. Parabolic Reflectors	740	24.1
60 ft. Parabolic Reflectors	450	12.7

The above values will be used in further discussions; however, any other frequency-power combination from the curves could have been used.

From the analysis of a large quantity of measured data (120 radio paths, with up to three years³ data) the distribution of hourly median values of field strength (or basic transmission loss) with reference to the time block 2 medians has been determined and plotted

* Actually the optimum frequency for this type of antenna may be below 70 Mc; lower frequencies are not considered in this study because of practical limitations such as non-availability of spectrum space.

on Figs. 2 - 12 of Ref. 1 for the individual time blocks, as well as for all hours of the year combined. The latter is included here as Fig. 4. These empirical distributions are functions of the angular distance θ ; thus the ordinate values $V(p, \theta)$ indicate the number of decibels which must be subtracted from the winter afternoon transmission loss values L_{bm} to obtain the expected transmission loss value L_{bmp} for at least $p\%$ of all hours of the year over the path characterized by a given θ :

$$L_{bmp} = L_{bm} - V(p, \theta) \quad (2)$$

The same relation holds for the required transmitter power; thus

$$P_t = P_m - V(p, \theta) \quad (3)$$

gives the value of transmitter power expected to provide the desired grade of service during at least $p\%$ of all hours of the year. For the example used, the angular distance θ is 40.2 milliradians for the 60 ft. parabolic antennas (with their radiation centers assumed to be 35 ft. above ground). The distribution of the $V(p, \theta)$ values for $\theta = 40.2$ may be read from Fig. 4. Values of $V(p, \theta)$ selected for various percentages of time, p , are substituted in (3) to obtain a distribution of P_t as shown in Fig. 5. In Fig. 5, P_m is taken as 12.7 db from the table above for the optimum 450 Mc frequency. Log-normal graph paper is used and the points plotted are connected by a smooth curve, which is the cumulative distribution of transmitter power values P_t as a function of the percentage of hours p . Similar distributions may be obtained using other values of P_m from the table on p. 7 or directly from Fig. 3. Thus Fig. 5 shows the amount of transmitter power expected to provide the specified grade of service or better during the percentage of hours indicated by the abscissa; as an example, for 60 ft. dishes at 450 Mc, 100 watts (20 dbw) transmitter power would be expected to provide the specified grade of service or better during 99.62% of all hours, as the 20 dbw ordinate intersects the curve at the 99.62 abscissa value. This may also be termed the "time availability" of this specified grade of service as a function of transmitter power.

6. The Concept of Service Probability

Although Fig. 5 is a graph of time availability versus transmitter power of a specified grade of service, the design problem is still not completely solved. It must be remembered that the prediction formula for the hourly median basic transmission loss has empirical terms in it, and its comparison with data shows appreciable deviations of predicted from observed values. There are factors influencing the transmission loss and thus the required transmitter power which are not taken into account by the prediction formula, because it is impracticable to allow in more detail for the actual characteristics of the terrain and the atmosphere and because of uncertainty in the estimate of the equipment performance terms F and R . Therefore, if we consider a number of tropospheric propagation paths having identical geometrical and meteorological parameters entering the prediction formula, and resulting in the same predicted all day-all year distribution of hourly-median basic transmission loss (or required transmitter power, similar to Fig. 5), an extensive long-term measurement program for all those similar paths would result in a range of all day-all year distributions as well as in a range for the long-term overall medians rather than in a single result. It may be assumed that all of those measured long-term overall median values are normally distributed about the calculated value; similarly, any percentage point of the all day-all year distributions will also be characterized by a distribution of measured values about the calculated value. Thus the calculated all day-all year distribution is an "expected" distribution in the usual statistical meaning of the term.

A substantial amount of work has been performed in comparing calculated and measured data. Some of the results are shown in an earlier paper^{6/}; on the basis of these results and of others obtained since, estimates have been made of the prediction uncertainty as

^{6/} K. A. Norton, P. L. Rice, and L. E. Vogler, "The use of angular distance in estimating transmission loss and fading range for propagation through a turbulent atmosphere over irregular terrain," Proc. IRE, 43, No. 10, pp. 1488 - 1526, Oct. 1955

explained above for time block 2 (long-term) medians, and of other percentage values. The prediction uncertainty for the time block 2 medians may be characterized by a standard deviation $\sigma_m = 5$ db if there is no substantial contribution to the received field strength by the diffracted mode. For short paths where the diffracted mode dominates, σ_m is taken as 6 db.

In order to obtain values of standard deviation which are applicable to all hours of the year, and for percentage points other than the median, a substantial number of available field strength measurements have been analyzed, as described in more detail in the Appendix. This analysis resulted in standard deviation values $\sigma_c(p)$ which characterize the prediction uncertainty for $p\%$ of all hours of the year. Curves of $\sigma_c(p)$ versus p are shown on Fig. 6 by the dashed curves (a) and (c).

The uncertainty in estimating the equipment performance parameters F (effective noise figure) and R (median r.m.s. carrier to median r.m.s. noise ratio required) may also be expressed by a standard deviation σ_r taken to be equal to 2 db in the absence of sufficient test data. The total prediction uncertainty for $p\%$ of all hours may thus be characterized by a standard deviation $\sigma_{rc}(p)$, which is given by

$$\sigma_{rc}^2(p) = \sigma_c^2(p) + \sigma_r^2 \quad (4)$$

under the reasonable assumption that the variables concerned are uncorrelated.

$\sigma_{rc}(p)$ as a function of the percentage of hours p is shown by the solid curves (b) and (d) of Fig. 6 for $\sigma_m = 5$ db and 6 db and $\sigma_r = 2$ db.

The concept of prediction uncertainty is expressed in terms of the probability of obtaining a given time availability of the specified grade of service or better for a particular path. This is a measure of the chance of success for the path, and may be termed "service probability." A "double probability" graph paper is used, where probability scales are used for both the abscissa and the ordinate. Values of service probability are obtained by combining the all day-

all year distribution of expected transmitter power values (Fig. 5) with the standard deviation $\sigma_{rc}(p)$ as shown below. The method is based on the assumption that the errors are normally distributed as discussed above.

Let $F(t)$ denote service probability as plotted along the abscissa scale on a double probability graph paper such as shown on Fig. 7. The ordinate scale is labelled "time availability," and is expressed in $p\%$ of all hours. The system power $P[F(t), p]$ required to provide the specified grade of service or better during $p\%$ of all hours with the probability $F(t)$ may now be related to the expected value of system power $P(0.5, p)$ by

$$P[F(t), p] = P(0.5, p) + t \cdot \sigma_{rc}(p) \quad (5)$$

where
$$F(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^t e^{-z^2/2} dz \quad \text{and } t \text{ is a standard}$$

normal deviate, while $\sigma_{rc}(p)$ has been defined above. It should be noted that t is assumed to be normally distributed whereas the distribution of L_{bm} with time is assumed to be as given in Ref. 1.

To illustrate the use of (5) we will calculate the power, $P(0.95, 99)$, required with 60 ft. dishes at 850 Mc to provide the specified grade of service or better for 99% of the hours with a probability of success equal to 0.95. This is readily determined from (5) by reading the value $P(0.5, 99) = 21.3$ db on the appropriate curve (Fig. 5) and adding to this $1.645 \times 6.38 = 10.5$ db resulting in a value of $P(0.95, 99) = 31.8$ db above one watt. Table II gives the values of t vs $F(t)$ while the value $\sigma_{rc}(99) = 6.38$ db was obtained from curve (b) of Fig. 6.

Table II

<u>F(t)</u>	<u>t</u>
0.50	0
0.70	0.524
0.90	1.282
0.95	1.645
0.98	2.054
0.99	2.326
0.995	2.576
0.998	2.878
0.999	3.090

We can also determine the service probability $F(t)$ as a function of p for some fixed value P_o of transmitter power, such as 1, 5 or 10 kilowatts, by setting $P[F(t), p] = P_o$ in (5) and solving for t :

$$t = \frac{P_o - P(0.5, p)}{\sigma_{rc}(p)} \quad (6)$$

Note that t is simply a function of p and that $F(t)$ can be determined as a function of t from appropriate probability tables^{7/}. As an example Table III gives the calculations of $F(t)$ versus p for $P_o = 30$ dbw with 60 ft. dishes at 850 Mc.

^{7/} C. A. Bennett and N. L. Franklin, "Statistical analysis in chemistry and the chemical industry," John Wiley and Sons, Inc., New York, 1954. See p. 86 and Table I of Appendix (pp. 689-693)

Table III

Service Probability Calculations

(1)	(2)	(3)	(4)	(5)	(6)
Time Avail- ability p, in percent of all hours	$P(0.5, p)$ in db	$P_o - P(0.5, p)$ in db	$\sigma_{rc}(p)$ in db	t	$F(t)$
99.99	26.8	3.2	7.70	0.416	0.661
99.9	24.1	5.9	7.06	0.836	0.798
99	21.3	8.7	6.38	1.36	0.913
95	19.0	11.0	5.70	1.93	0.973
90	17.6	12.4	5.39	2.30	0.9893
70	14.5	15.5	5.15	3.01	0.9987

The values in column (2) of Table III were determined from Fig. 5 while the values in column (4) were determined from Fig. 6. Column (5) is obtained by dividing (4) into (3), and (6) is obtained from (5) by the use of the table of standard normal deviates. The resulting values of $F(t)$ are plotted as abscissa values to the ordinates p on the double probability display, and the points connected by a smooth curve, as shown on Fig. 7.

If the term $P_o = P(0.5, p)$ is negative, t will be negative, and the corresponding value of $F(t)$ less than 0.5. Using the table of Ref. 7, the value in the column headed $1 - F(t)$ is applicable in this case.

The smooth curves drawn on Fig. 7 are the final results of the study, and represent the relationship between service probability and the time availability of the specified grade of service. The intersection of the curve marked 60 ft. dishes - 850 Mc - 1 kw with the 99% ordinate, for example, determines an abscissa value of 0.91. This is the probability that the specified grade of service or better will be obtained during 99% of all hours by the use of the 850 Mc - 60 ft. dishes - 1 kw transmitter power combination.

If the operating frequency is lowered to 450 Mc, points for another service probability curve may be drawn using the 60 ft. dishes - 850 Mc data on Fig. 5 as a reference; this new curve for 450 Mc has also been plotted on Fig. 7 and shows that for the same 1 kw value of transmitter power the probability to obtain the specified grade of service or better during 99% of all hours is increased to 0.962.

Additional curves shown on Fig. 7 are for the other antenna types and frequencies considered, and were obtained from Figs. 5 and 6 with the aid of (5) and (5a) in the same manner as discussed above. It is quite obvious that each of the curves on Fig. 7 may be labelled with a dollar tag denoting installation, operation and maintenance cost; thus an estimate may be made of the additional cost necessary to obtain a greater probability of success; i.e., the increase from a 0.49 to a 0.94 probability shown for 28 ft. dishes at 740 Mc at 99% time availability is obtained by increasing the transmitter power from 1 to 10 kw. This means that the additional installation and operational expenses "buy" a better chance of obtaining the desired results. Fig. 7 shows also that for this particular path an increase in antenna size to 60 ft. (with a lowering of the operating frequency to 450 Mc) provides an even larger probability value than the transmitter power increase from 1 to 10 kw with 28 ft. dishes; thus the costs for the two possibilities may be compared on the basis of the service probability values read from the curves.

The first illustration of the use of (5) provides an alternate method in comparing different systems, or different paths. In some instances it will be of interest to fix the values of service probability and time availability as a basis for comparison, rather than to study the functional relationship illustrated on Fig. 7. In this way, fixed values of transmitter power are obtained, which will provide the specified grade of service or better during $p\%$ hours of the year with a probability of $F(t)$. This procedure has been used as additional examples for the systems considered in developing Fig. 7, and the results are given in Table IV below. A time availability $p = 99\%$ of all hours, and a service probability value $F(t) = 0.95$ were chosen as a basis for comparison. The latter represents a "19 out of 20 chance of success." If only this alternate method is used to compare systems without developing the service probability graphs, the 0.95, or a higher value of $F(t)$ should be chosen in order to provide an adequate margin of safety, especially if service is actually required for 99% of all hours.

Of course the entire risk versus cost picture is provided by diagrams such as Fig. 7 and this makes possible an intelligent determination of the best system to employ. For example, in some cases it may be desirable to install a lower powered system with the knowledge that inadequate performance which might occur by chance with this lower power can later be improved, or even over-corrected by the addition of a power amplifier.

Table IV

Required transmitter power for a 0.95 service probability of obtaining the specified grade of service during at least 99% of all hours of the year

System (all quadruple diversity)	$P(0.5, 99\%)$	$t \cdot \sigma_{rc}(p)^*$	$P(0.95, 99\%)$	
	dbw	db	dbw	kw
60 ft. dishes - 850 Mc	21.3	10.5	31.8	1.5
60 ft. dishes - 450 Mc	18.6	10.5	29.1	0.8
28 ft. dishes - 740 Mc	30.1	10.5	40.6	11.5
18 db antennas - 70 Mc	35.6	10.5	44.1	25.7

The relative cost of the various systems with the transmitter power values determined in this way may again be evaluated.

7. Conclusions

It has been shown how the performance of a communication system may be predicted and how the probability of its success may be evaluated by the introduction of the concept of service probability. Thus the accuracy of the predictions depends on the magnitude of the standard error values $\sigma_{rc}(p)$ and their component parts $\sigma_c(p)$ and σ_r . If $\sigma_{rc}(p)$ is reduced, the curves of Fig. 7 will be less steep, and the expected value ($p = 0.5$) would constitute a better estimate since it

* For the values given, t and $\sigma_{rc}(p)$ are constant at 1.645 and 6.38 db, respectively.

would not differ as much from the estimates for higher and lower values of p . The question whether the standard deviation $\sigma_{rc}(p)$ can be significantly decreased by taking into account the results of transmission loss measurement will be treated in a subsequent report, which will also include a study pertaining to the quantity of measured data necessary to obtain a worthwhile degree of improvement of the predictions.

8. Acknowledgements

The authors are indebted to Messrs. R. S. Kirby and J. W. Herbstreit for their careful review and their suggestions. Drafting work on the figures was done by Messrs. J. C. Harman, D. G. Harrison, C. R. Sandstrom, and Mrs. B. G. Bolton. The manuscript was typed by Mrs. M. J. Benedict.

APPENDIX

Prediction uncertainty is based on the variance $\sigma_C^2(p)$ of the difference between calculated and observed values of basic transmission loss, that is $L_{bc}(p) - L_{bo}(p)$. This variance is larger in the diffraction region than in the scatter region and is a minimum near the $p = 50\%$ value of time availability. Values of $\sigma_C^2(p) = 36 \text{ db}^2$ and 25 db^2 , respectively, were obtained in these two regions by comparing calculated and measured time block 2 medians (of hourly medians) for some 125 paths ranging in distance up to 630 miles and representing frequencies from 70 to 1050 megacycles. This variance is assumed to be representative of all day-all year conditions, though obtained from medians for a single time block.

Two more sets of data were used to check the assumption that the prediction error is on the average about the same for all hours as for a single time block:

(A) For time blocks 2 and 4 and for 70 paths of the 125 mentioned above, the mean square and variance of $L_{bc}(p) - L_{bo}(p)$ was determined for $p = 1\%, 10\%, 50\%, 90\%$, and 99% .

(B) For all hours and a total of 80 paths for two frequencies and two distance ranges (80 and 120 miles), the mean square and variance of $L_{bc}(p) - L_{bo}(p)$ was determined for the same values of p as in (A). The same variance study was done for time blocks 2 and 4, expected to represent fairly extreme conditions, and results were almost the same.

Ideally, estimates of $\sigma_C^2(p)$ should be based on a comparison of observed and calculated values $L_{bo}(p)$ and $L_{bc}(p)$ at each percentage level p for a wide diversity of propagation paths for which all day-all year cumulative distributions are available. Data set (A) represents a wide diversity of paths, but not all hours, and (B) represents all hours over a large number of paths which are located in a single region in Ohio.

Long-term recordings over a large number of paths would be needed to establish accurately $\sigma_C^2(p)$ for each possible combination of the prediction parameters. The mean error of prediction, or average "bias" of the prediction method will average to zero over the entire range of propagation path parameters represented by the available

data, but this bias is not expected to be zero in a given region for given values of distance, angular distance, antenna height, frequency, and surface refractivity. Here, the mean square deviation of observed from predicted values of transmission loss, $\sigma_C^2(p)$, is the sum of (1) a variance about the mean prediction error and (2) the square of this bias.

The variance of prediction error about its mean value in the scatter region was assumed independent of all prediction parameters except p and was estimated from data set (A), observed and predicted values for $p = 1\%$, 10% , 50% , 90% , and 99% of all hours corresponding to two Ohio FM stations, each recorded for one year at 80 and 120 miles over a total of 80 propagation paths. The first row of Table I-1 lists the average values for these variances as a function of the time availability p .

The mean square error of prediction for time blocks 2 and 4 is listed in row 2 of Table I-1, averaging values for 70 paths at each percentage level (data set (B)). Tentative estimates of $\sigma_C^2(p)$ appear in row 3 of Table I-1, as the sum of variance and mean square bias from rows 1 and 2. Rows 4 and 5 show the final variances adjusted to 25 and 36 db^2 , respectively, at $p = 50\%$, and the corresponding standard deviations are given in rows 6 and 7. These standard deviations $\sigma_C(p)$ are plotted versus the time availability p in Fig. 6 for the diffraction and scatter regions; this measure of prediction uncertainty is used to determine service probabilities as a function of p , as explained in the body of the text.

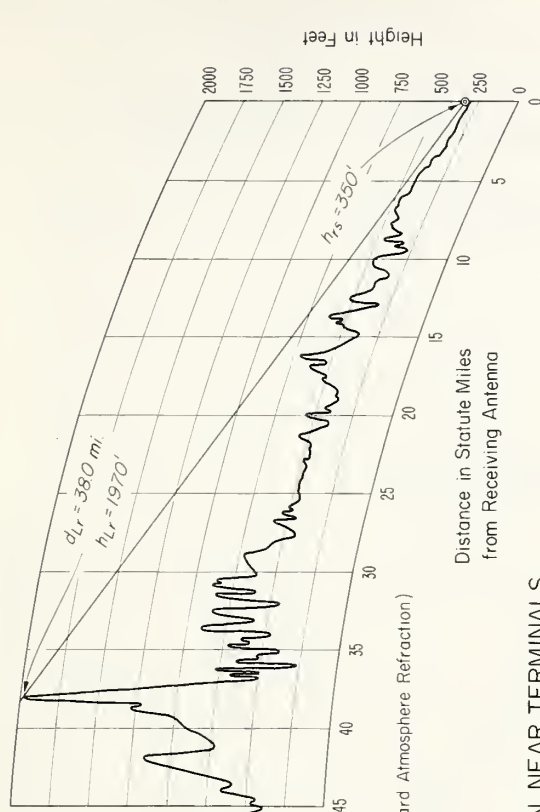
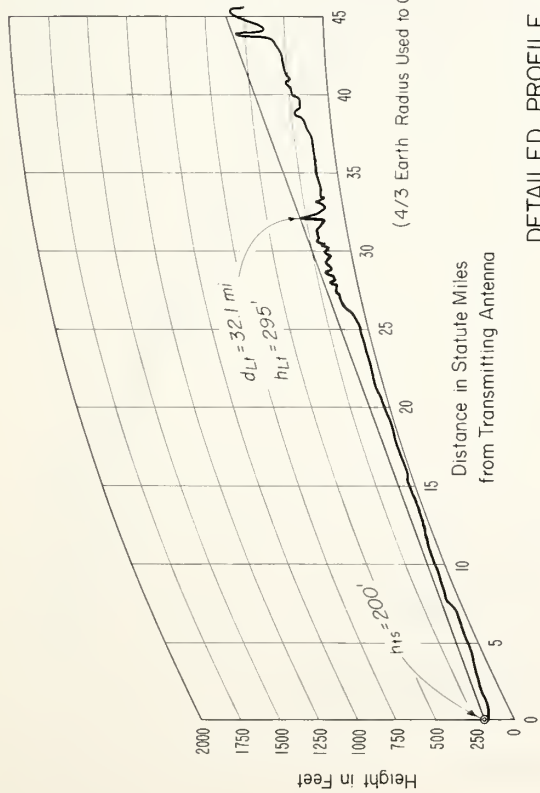
Table I-1

Steps used in estimating standard deviations $\sigma_c(p)$

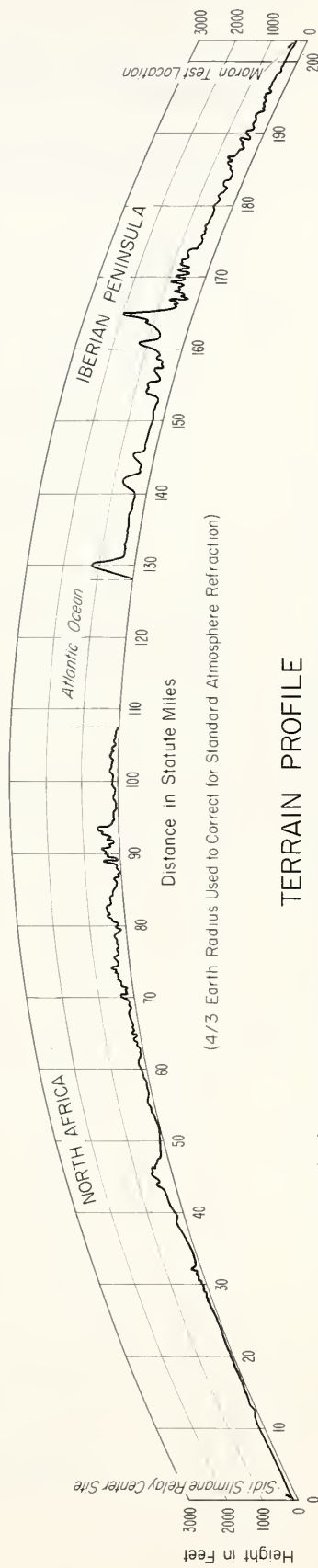
	$(db)^2$ for percent of all hours			
	<u>1</u>	<u>10</u>	<u>50</u>	<u>99</u>
(1) Average variance from Ohio data	69.443	39.073	19.809	19.030
(2) Mean square bias from TB 2 and TB 4 data	1.364	0.509	0.286	1.034
(3) Sum of (1) and (2) above	70.807	39.582	20.095	20.064
(4) (3) adjusted to $\sigma_m^2 = 25.00 (db)^2$	75.712	44.487	25.000	24.969
(5) (3) adjusted to $\sigma_m^2 = 36.00 (db)^2$	86.712	55.487	36.000	35.969
				47.870

Standard deviations $\sigma_c(p)$ in db for percent of all hours plotted on Fig. 6 as curves (a) and (c)

(6) $\sigma_m = 5.0$ db	8.70	6.67	5.00	4.99	6.06
(7) $\sigma_m = 6.0$ db	9.32	7.45	6.00	6.00	6.92



DETAILED PROFILE OF TERRAIN NEAR TERMINALS



TERRAIN PROFILE SIDI SLIMANE RELAY CENTER SITE TO MORON TEST LOCATION

Figure 1

CALCULATED MEDIAN BASIC TRANSMISSION LOSS VERSUS
FREQUENCY FOR AVERAGE TIME BLOCK 2
(WINTER AFTERNOON) HOURS
Sample Path Sidi Slimane (SSC) to Moron (A)

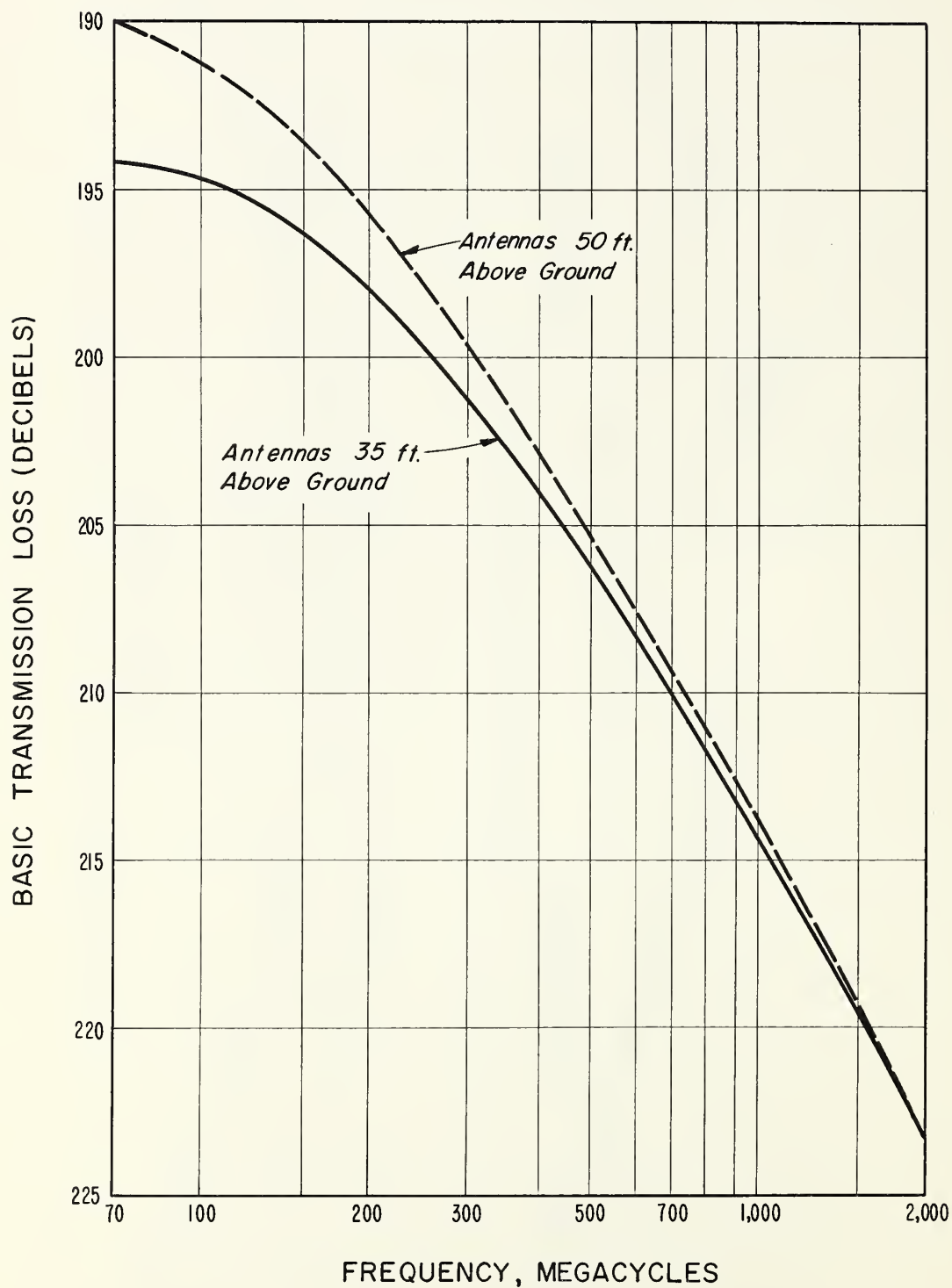


Figure 2

TIME BLOCK 2 MEDIAN TRANSMITTER POWER VERSUS
FREQUENCY FOR VARIOUS TYPES OF ANTENNAS
FM system, quadruple diversity
Sidi Slimane - Moron Path

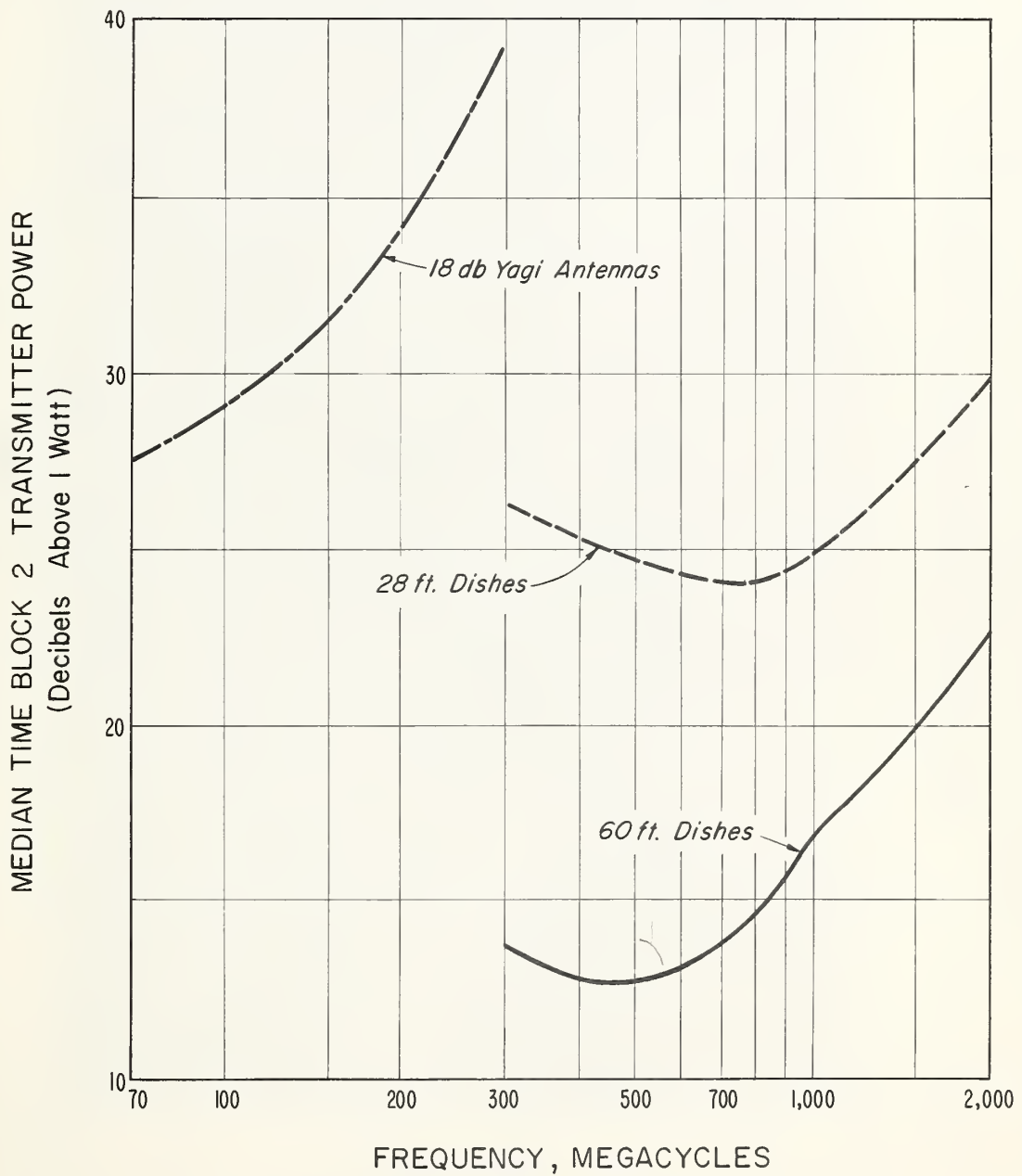


Figure 3

EXPECTED SIGNAL LEVEL, $V(p, \theta)$, EXCEEDED BY p PERCENT OF ALL HOURLY MEDIANS
OBSERVED AT ANGULAR DISTANCE θ DURING ALL HOURS OF THE YEAR

$V(p, \theta)$ shows the deviation of all-day, all-year values, $L_b(p, \theta)$,
relative to median basic transmission loss, L_{bm} , for the period
November - April, 1 P.M. - 6 P.M. (Time Block No.2)

$$L_b(p, \theta) = L_{bm} - V(p, \theta) \text{ decibels}$$

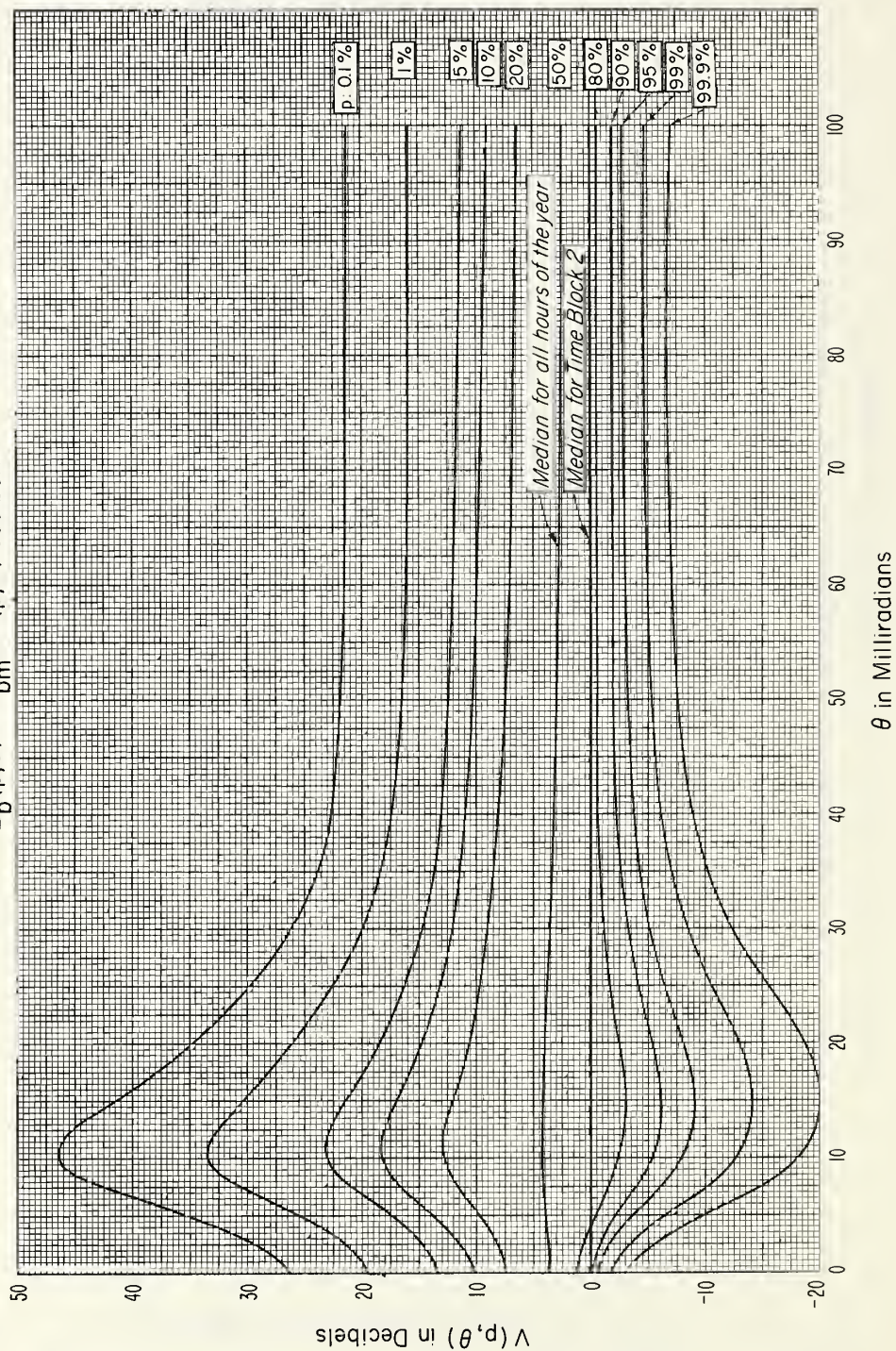


Figure 4

TRANSMITTER POWER EXPECTED TO PROVIDE A SPECIFIED GRADE OF SERVICE
FOR AT LEAST THE PERCENTAGE OF HOURS OF THE YEAR INDICATED BY THE ABSCISSA

FM system, quadruple diversity

Sidi Slimane - Moron Path

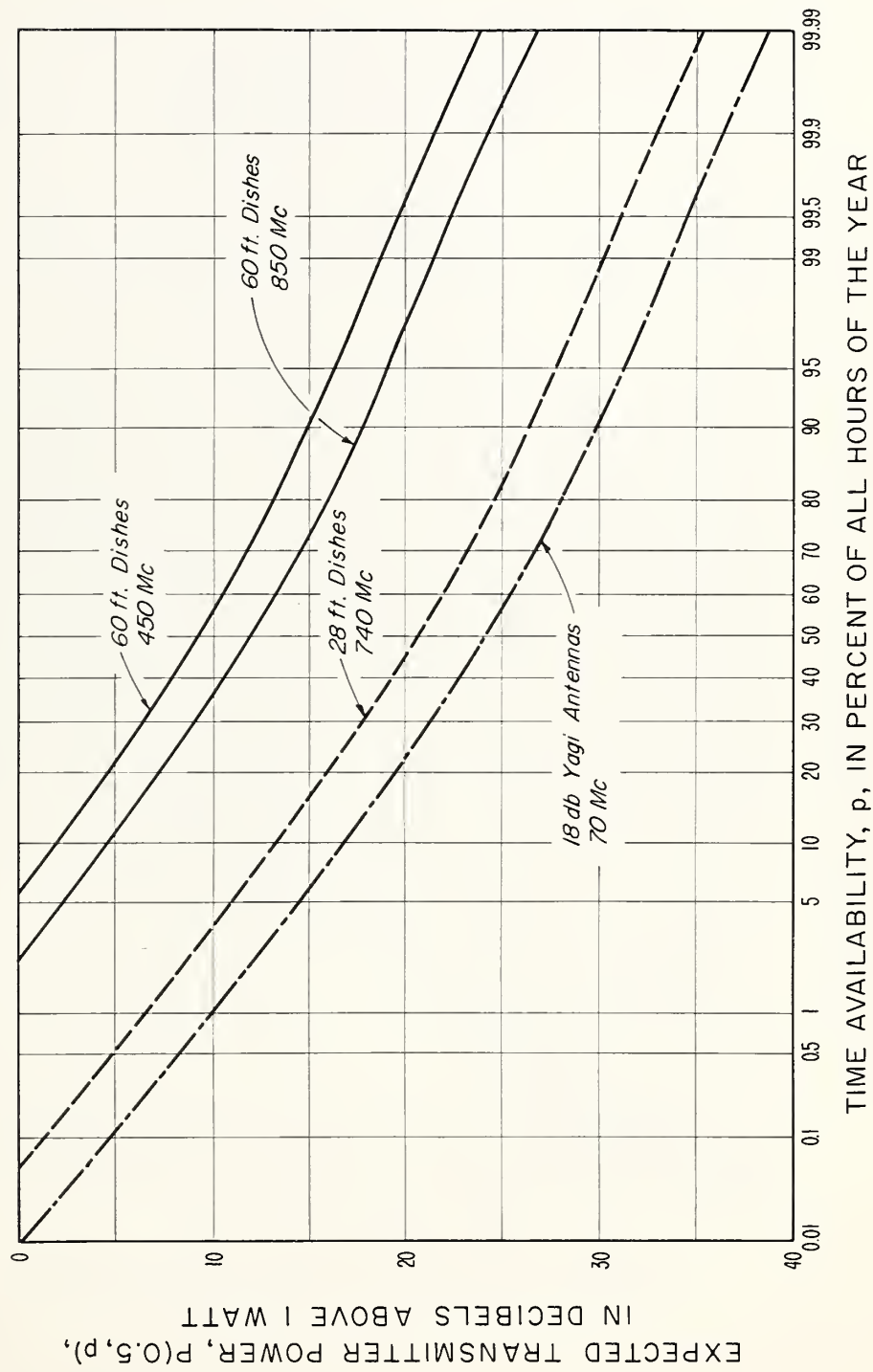


Figure 5

ESTIMATED PREDICTION UNCERTAINTY FOR ALL HOURS OF THE YEAR EXPRESSED BY STANDARD DEVIATIONS

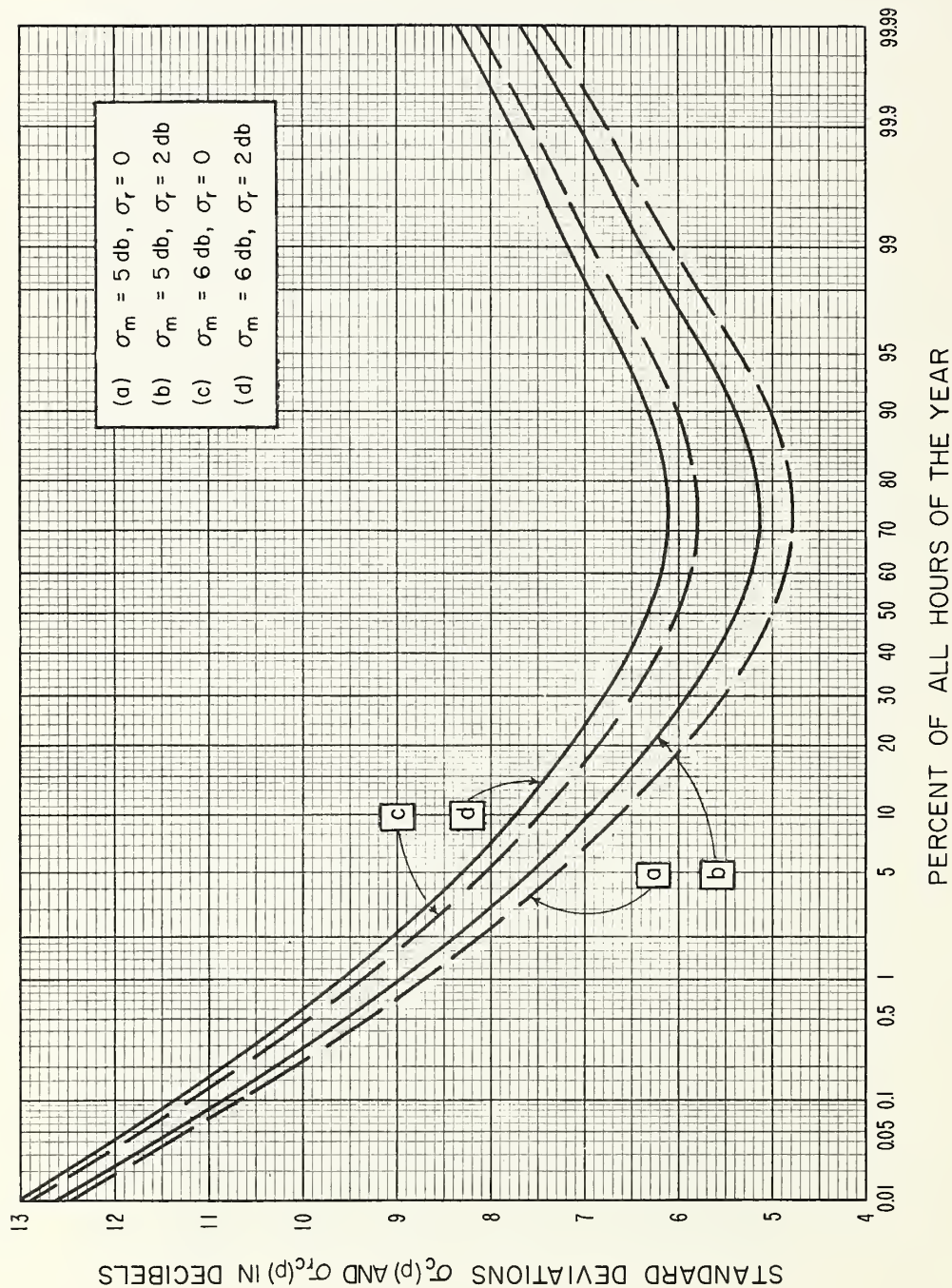


Figure 6

SERVICE PROBABILITY FOR
QUADRUPLE DIVERSITY FM SYSTEMS
SIDI SLIMANE TO MORON
24 VOICE CHANNELS

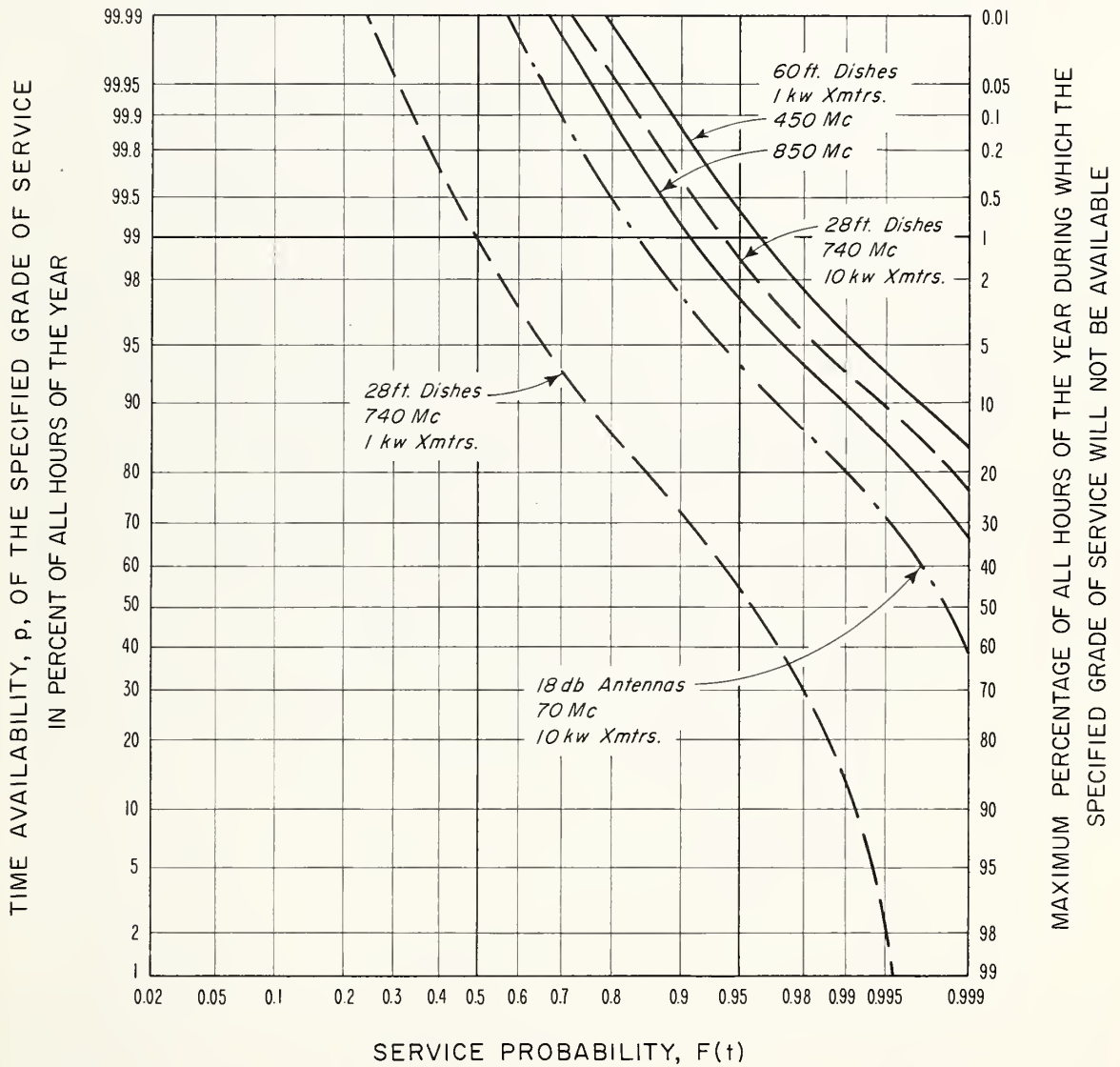


Figure 7

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